

Engineering Dependability Requirements for Software-intensive Systems through the Definition of a Common Language

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Abstract

Engineering dependability requirements for software-intensive systems is inherently difficult. Dependability of these systems relies heavily on the emergent properties that result from the complex interdependencies that exist among the involved systems and their environments. Furthermore, the choice of a modeling technique significantly affects the semantics and the level of abstraction at which these systems are modeled and analyzed. Therefore, to effectively predict the emergent properties of the system as a whole, it is necessary to gather information based on multiple philosophies from complementary modeling techniques and analyze them in the context of each other. To realize such a unified approach during the early stages of the RE lifecycle, we advocate the need for the definition of a common language. The common language provides a framework within which several modeling techniques can be used in harmony to elicit and create a common understanding through the problem domain concepts, properties and their relationships. We provide examples from our case study on automating the standard Department of Defense Information Technology Security Certification and Accreditation Process (DITSCAP) to motivate the applicability and appropriateness of our approach.

1. Introduction

We are witnessing ever more reliance on “systems of systems” that have emerged as complex amalgamations of underlying software, systems, practice, and environment in government as well as industry. The wide-spread use of such systems in critical applications that range from embedded process controls with mostly solid-state static interfaces to large-scale information infrastructures operational in dynamic socio-technical environments requires them to exhibit compelling evidence that their services satisfy

certain dependability properties [29]. Such dependability is mostly expressed in terms of safety, security, availability, and reliability dimensions [36]. As we start to consider these dimensions for *systems of systems*, we realize that they rely heavily on the characteristics and capabilities of the system working as a whole to satisfy their real world goals and objectives. In essence, dependability along with other non-functional and functional features arises from the emergent properties exhibited by the collective influences of individual systems on each other as well as their propagative effects throughout the system. Such influences build a cluster of closely interdependent systems of systems. In the class of such systems, the ones in which software offers a significant portion of the system functionality are commonly referred to as software-intensive systems [38].

Software-intensive systems that are operational in socio-technical environments typically involve interactions between software, hardware, people, data, physical spaces, organizational policies, standards, procedures, laws, and regulations. Naturally in such multi-faceted environments, emergent properties which affect dependability are inherently difficult to understand and predict. Emergent properties can provide unanticipated benefits or can deviate from required capabilities of the system. In all cases, emergent properties make predictions about dependability, which is potentially the greatest risk to software-intensive systems [3].

The key challenges in engineering dependability requirements for software-intensive systems can be summarized as: 1) Difficulty in understanding the complexity of the relationships between diverse system components in a socio-technical environment; 2) Difficulty in establishing the extent to which dependability requirements satisfy their real-world goals and objectives; 3) Emergent properties of the system as a whole influence dependability; 4) Multitude of dependability requirements and their interdependencies; 5) Varying semantics and levels of

abstractions in specifying dependability requirements based on different methods and techniques; and 6) A wide-range of system/service stakeholders that address and evaluate dependability attributes from different perspectives. Also, these issues further cause breakdowns in communication between stakeholders as well as porting of information from one RE stage to another [7].

We contend that to address these challenges and their diversity, software-intensive systems require RE methods based on multiple philosophies from complementary modeling techniques to elicit and capture several dimensions of the problem domain. Individual modeling techniques are effective for capturing certain aspects of the system but themselves cannot guarantee the accuracy and comprehensiveness of the predicted emergent behavior. Therefore, to effectively predict the emergent properties of the integrated system it is necessary to gather information based on multiple philosophies from complementary modeling techniques and analyze them in the context of each other. We believe that the lack of a comprehensive and well-defined framework that can accommodate different philosophies, methods and techniques for modeling and analysis of dependability requirements is at the root of the problem. To address this issue, we contend that the definition of a *common language* is required during the early stages of the RE lifecycle. Such a common language provides a framework within which complementary philosophies and associated modeling techniques can be used in harmony to elicit and create a common understanding through the problem domain concepts, properties and relationships in the Universe of Discourse (UofD). As one would expect, the definition of such a common language requires a rich set of representations, modeling techniques and tools as well as systematic ways to collect and organize the necessary information, i.e. the *Science of Design* of engineering quality dependability requirements for software-intensive systems.

In this paper, we present an integrated and comprehensive framework which combines novel techniques from RE and knowledge engineering to define and utilize a common language during the early stages of RE. Within the framework we also introduce the concept of Multi-Dimensional Link Analysis (MDLA) that supports early identification/prediction of emergent properties that affect dependability, by means of its traceable rationales and tool support. We understand that different dimensions/types of dependability attributes are interrelated [16], but we currently focus on the security dimension through examples derived from our case study [20] on automating the DITSCAP [12].

2. The Definition of a Common Language

We believe that in order to engineer quality (co-operative, comprehensive and cost-effective) dependability requirements, it is necessary to capture a holistic view of the system. Such a view includes relationships between system attributes, the environment and the nexus of causal chains [18], spanning several dimensions and levels of abstractions that exist to satisfy the real world goals of the associated users, business and organization. Understanding user needs within the context of the proposed system and as part of the wider organizational setting can greatly increase the accuracy and completeness of real-world requirements [7]. Furthermore, for critical operations, early reflections on the emergent system properties are necessary to predict whether the eventual system behavior will be dependable or not. In the following subsections we outline the characteristics and components of a common language that embodies a comprehensive view of the system under consideration.

2.1. Building a Common Language

Ideally, the definition of a common language should encompass all dimensions of a problem domain, captured at various levels of abstractions from diverse viewpoints. Although such expressiveness in representation is practically infeasible, we use hierarchical organization of ontological concepts to capture several key dimensions of the problem domain with related properties and non-taxonomic dependencies among them. The ontological concepts, their properties and relationships are elicited from various sources using RE modeling methods and techniques that is most suitable. During the early phases of RE, such ontological concepts are elicited from users, natural-language documents, requirements enforced through standards, various taxonomies in the domain, transcripts, organizational policies, domain knowledge, environmental constraints, laws and regulations, etc. Finally as the higher level ontological concepts become available, they are instantiated at the leaf-node level with specific criteria that help in gathering the related user/system information. These leaf-nodes provide a way to establish the extent to which the higher-level abstractions are satisfied through specific policies, procedures or technical rationales in the actual environment. Figure 1 provides an overview of the various levels of abstractions in the definition of a common language. Such a structured organization of the problem domain knowledge has several benefits: 1) It provides the definition of a

common language for interoperability and communication at various levels of abstractions; 2) Allows the projection of a system-wide view while analyzing requirements; 3) The level of completeness of the common language gives a clear indication of areas of the problem domain that require further exploration; 4) It provides traceability among concepts in the problem domain to understand their inter-dependencies.

As shown in Figure 1, the integral part of our framework is a Problem Domain Ontology (PDO) that provides the definition of a common language. The PDO is a machine understandable, hierarchical representation, engineered using object-oriented ontological modeling techniques. The PDO construction leverages knowledge engineering techniques to support meta-knowledge creation, representation and processing. It also provides the ability to query and browse structured information sources based on inference mechanisms. The inherent benefits of such a PDO lie in the uniformity of its representation allowing for its use, reuse and evolution through all stages of the RE lifecycle.

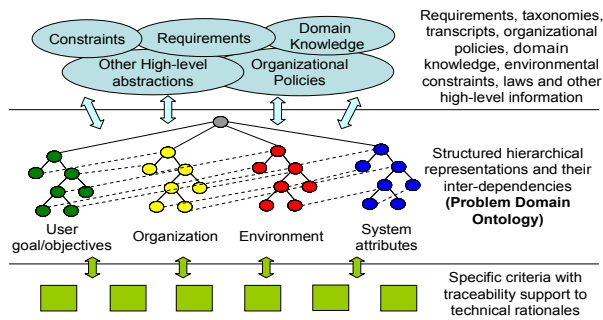


Figure 1: Information at various levels of abstractions in a Common Language

The PDO is modeled based on the GENeric Object Model (GenOM) [23]. GenOM is an integrated development environment for ontological engineering processes with functionalities to create, browse, access, query and visualize associated knowledge-bases. GenOM inherits the theoretical foundation of the frame representation and is compatible with the OKBC specification [6] as well as the OWL representation [28] format. GenOM's rich modeling constructs coupled with easily understandable semantics make it an optimal choice for the creation of a common language with participation from diverse stakeholders and experts in the UofD. The conceptual architecture of GenOM is shown in Figure 2.

The GenOM meta-language consists of *objects*, *properties*, and *features* with semantics that effectively support knowledge acquisition and representation.

GenOM *objects* can be used to describe the concepts in a domain. It also supports modeling of hierarchical structures by single or multiple inheritance mechanisms. GenOM *properties* are used to describe the characteristics or attributes of *objects* and *features*. Finally, GenOM *features* are used to describe the relationship or dependencies that exist between objects. Once the objects, properties and features are defined, they are instantiated to represent specific instances that exist in a problem domain. GenOM is also associated with an inference engine [4] which supports reasoning based on the *objects*, *properties*, *features* and *instances* defined in its knowledge-bases. In summary, GenOM supports object modeling in its representation, usage of objects in its application model, and ability to aggregate evidence that supports the analysis of objects' behaviors (through the associated properties and relationships between objects).

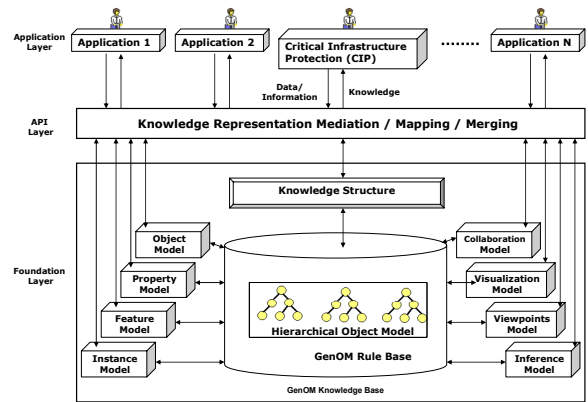


Figure 2: GenOM Conceptual Architecture

2.2 The Components of a Common Language

To systematically capture various aspects of the problem domain through the definition of a common language, we employ several popular and well-studied RE philosophies, methods and techniques. Specifically, we focus on RE modeling techniques based on the notions of goals [40], viewpoints [15], scenarios [5], and their combinations. Before outlining the fundamental models and techniques for the creation of a common language, we provide a brief introduction to DITSCAP [12], which will help in presenting these models using examples from the DITSCAP domain. DITSCAP examples focus on the security dimension of dependability requirements.

The role of DITSCAP is to maintain information assurance and the security posture of the Defense Information Infrastructure (DII) throughout the life-cycle of the information systems contained in it. DITSCAP focuses on the system mission,

environment, architecture, and life cycle while assessing the impact of operation of the information system on the overall security posture of the DII [19]. In a nutshell, the motivation of DITSCAP is to identify and evaluate information security requirements applicable to the target system; outline a set of activities for performing Certification and Accreditation (C&A); generate required documentation; provide security solutions; and manage information system security activities. The DITSCAP problem domain is an ideal venue to study critical software-intensive systems, as it consists of systems which connect Department of Defense (DoD) mission support, command and control, and intelligence computers and users through voice, data, imagery, video, and multimedia services. These information processing and value-added services demand high quality of trust in the information furnished through them to the DoD and national-level decision makers.

We now introduce several models and techniques which systematically guide the creation of a common language in the DITSCAP domain.

2.2.1 Goal-driven Scenario Composition. RE techniques that combine the benefits of goal and scenario based approaches have been well researched [33] [26] [39]. To incorporate aspects of the system captured through these approaches in the definition of a common language, we present the goal-driven scenario composition technique. Following this technique, high level goals are successively decomposed into a set of specific goals whose realization criteria is captured using leaf-node scenarios. The goals in the hierarchy may express real-world goals of the system and its users; or from a process perspective, they can represent tasks and activities in a process. The leaf node scenarios capture specific user/system criteria related to the satisfaction of parent goals in the hierarchy. Such a goal-driven composition of scenarios helps in establishing their coverage over the problem domain concepts in addition to restricting their scope.

In the DITSCAP problem domain, goals of the C&A process are extracted from the homogenous groupings of well-defined tasks and activities outlined in the DITSCAP Application Manual [11]. The resulting hierarchical representation of the overall C&A process systematically guides the user through the DITSCAP. Furthermore, the leaf node scenarios employ carefully designed questionnaires that elicit user/system information required to identify the applicable DITSCAP-oriented security requirements as well as generate DITSCAP related documentation. To elaborate in further detail, we present an example where the security requirement of “Network Boundary

Defenses” i.e. firewalls installed at appropriate places in a network, is being analyzed for a target system. Figure 3 outlines a path through the C&A goal hierarchy that will lead to a systematic exploration of the concepts related to this security requirement. The specific criteria gathered through the leaf-node scenarios also helps to prune the search space identified by the goals over DITSCAP-oriented security requirements.

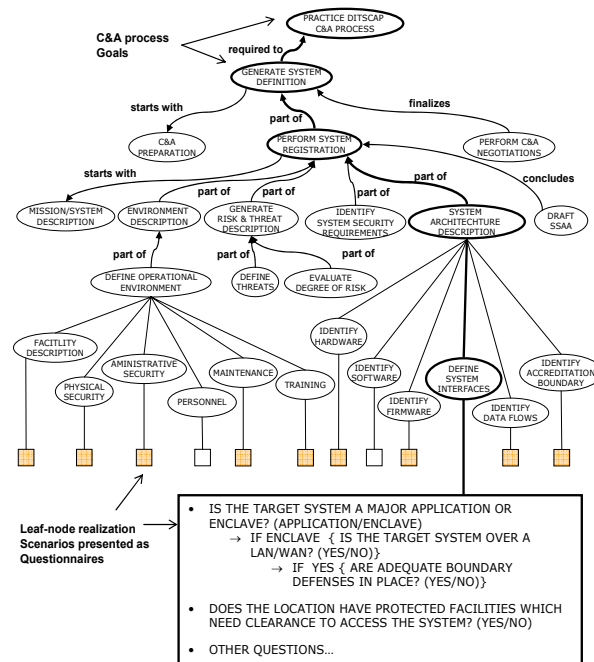


Figure 3: Partial DITSCAP C&A Goal Hierarchy

2.2.2 Requirements Domain Model (RDM). The RDM provides a systematic way to capture the problem domain requirements, their properties and inter-dependencies in the UoFD. The RDM follows a hierarchical representation format that includes top-level generic requirements, mid-level domain spanning requirements and leaf-node sub-domain requirements. Such an organization of requirements allow for their exploration to be conservative in nature i.e. to be more inclusive rather than exclusive of aspects that need to be considered in early stages of the RE lifecycle. All requirements in the hierarchy also have several attributes that capture information about their descriptions, source, stakeholders, keywords, and dependent requirements. The sources of requirements in the RDM can be natural-language requirements, requirements from C&A standards, taxonomies, transcripts, manuals, organizational policies, domain knowledge, environmental constraints, laws and regulations and other domain-specific requirements sources. Apart from hierarchical relationships, there

stakeholders associated with a software-intensive system. Viewpoints [15] provide an effective way to organize the diversity of factors associated with the requirements in the RDM. In a viewpoints hierarchy, the higher level non-leaf nodes in the hierarchy consists of viewpoints, such as organizational viewpoints which map to generic and mid-level requirements in the RDM, and the leaf nodes usually represent viewpoints such as those of specific system stakeholders, services or concerns that are related to specific requirements in the leaf nodes of the RDM. To further elaborate on the requirement for “boundary defenses” in our example, Figure 5 outlines the various stakeholders identified from a viewpoints hierarchy in the DITSCAP PDO. The viewpoints in the DITSCAP domain are identified from the roles and responsibilities of various stakeholders related to requirements in DITSCAP-oriented documents.

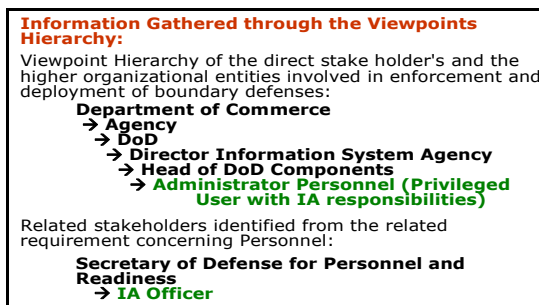


Figure 5: Information from a Viewpoints Hierarchy

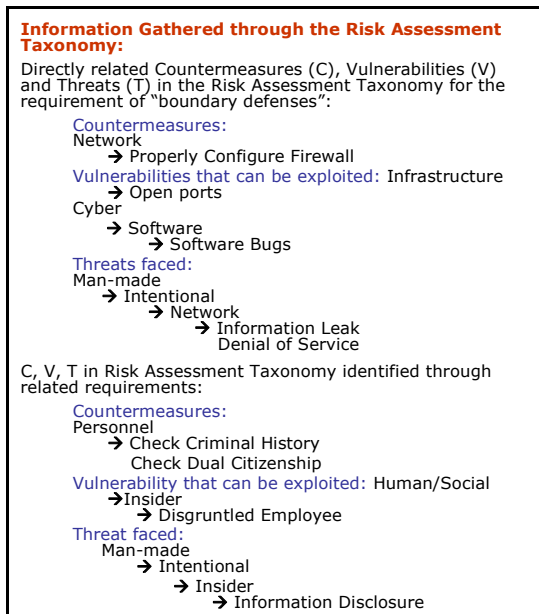


Figure 6: Information from a Risk Assessment Taxonomy in the DITSCAP domain

In the DITSCAP PDO we also include a *risk assessment taxonomy* which aggregates a broad spectrum of possible categories and classification of risk related information from the DITSCAP domain. The upper level nodes of the risk assessment taxonomy consist of threat, vulnerabilities, countermeasures, asset properties, and mission criticality concepts related to risk assessment. Each node is then further decomposed into more specific categories. In addition, several non-taxonomic links identify relationships within risk categories as well as with other entities in the DITSCAP PDO.

A risk assessment taxonomy is necessary to better understand security requirements as they naturally relate to various concepts of risk [21]. Such relationships can be discovered from various sources such as security requirements descriptions, research literature, taxonomies or from domain experts. Figure 6 depicts the risk information gathered for the requirement of “boundary defenses” used in our example, based on such relationships.

3. Multi-Dimensional Link Analysis

Examples in the previous section demonstrate how several core pieces of information that affect the emergent properties of the system can be systematically identified from the definition of a common language and its underlying models. In the DITSCAP domain, identification of such properties contributes to strengthen and effectively estimate the security dimension of system dependability.

Once the required pieces of information have been gathered from the PDO, they finally become valuable knowledge when they establish ‘links’ with each other from various aspects/dimensions based on a certain set of goals [22]. Following this paradigm, we introduce the concept of MDLA which can be triggered from different dimensions such as user criteria, viewpoints, system goals, scenarios, business/mission requirements, regulatory requirements, and risk categories. Such knowledge helps to understand the complex interdependencies and causal chains that exist between the real world goals, objectives and the components of a software intensive system. The PDO naturally fosters such analysis through the hierarchical organization of ontological concepts captured using several complementing RE modeling techniques. It increases the cohesiveness of information from various dimensions and provides inherent properties of an active approach to link requirements with other entities in the environment. Such an integrated framework for analytical analysis promotes a comprehensive coverage of the system’s dependability attributes and

systematically drives their elicitation, modeling and analysis by actively assisting in the process of discovering missing, conflicting, and interdependent pieces of information. A conceptual overview of MDLA in the DITSCAP domain is presented in Figure 7. It clearly demonstrates how different aspects of a requirement can be identified and analyzed within the framework of a common language based on information gathered from diverse system models with complementary semantics.

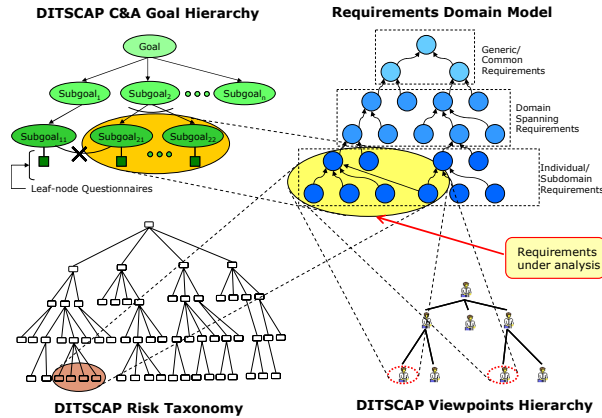


Figure 7: Conceptual overview of MDLA in the DITSCAP PDO

4. Related Work

For critical software-intensive systems, formal methods have often been used to provide a priori evidence that the overall system behavior will be dependable [8]. Apart from being costly, formal approaches are not very effective to gain a common understanding during the early stages of RE. Their complexity also limits participation of stakeholders with diverse skills and expertise. Through the definition of a common language we seek to gather contributions from several information sources and provide an early opportunity for analyzing the emergent system behavior.

Throughout the RE lifecycle several, several approaches exist to elicit and model dependability requirements which are primarily driven by illicit usage or threat scenarios captured using misuse/abuse cases [35] [1], abuse frames [25], intruder anti-goals [41], or attacker modeling and analysis [27], but they uncover only a limited set of dependability attributes based on the current context of analysis. The use of general taxonomies [16] [17], attack patterns [30] and threats [34] to derive security and survivability requirements can contribute to the refinement and elaboration of ontological concepts in the PDO.

However, we envision the classification and categorization of ontological concepts in the PDO to be primarily based on information gathered from the problem domain.

The LEL approach [24] was one of the first initiatives to support the elicitation and representation of a lexicon based on natural language processing, but the lexicon itself does not carry any information unless it is instantiated using a conceptual model. Currently, the use of a LEL to construct machine understandable ontologies resulting from the RE process, has been pointed out in [2]. Recent efforts for ontology based object-oriented domain modeling have also been expressed in [14].

We believe that the development of a common language in the early stages of RE, should not be restricted to specific modeling notions, constructs, or techniques as it may become too narrow-focused or stove-piped. Through our framework, we also strive to offer the flexibility in choosing the method or technique for RE that is most suited for the need of the situation, skills of the people involved or the uniqueness of the domain.

5. Conclusion and Future Work

Our contributions in this paper can be summarized as follows. Firstly, we identify specific issues in engineering quality dependability requirements for critical software-intensive systems, which motivate the need for the definition of a common language. Secondly, we present a comprehensive framework that integrates novel methods and techniques for the creation and utilization of a common language during the early stages of RE lifecycle. Examples presented throughout the paper demonstrate how several system models produced within the framework can be used in harmony to elicit and create a common understanding through the problem domain concepts, properties and their relationships. Finally, we introduce the concept of MDLA, which provides the ability to analyze different aspects of a requirement based on the information gathered from various system models available in the framework.

We believe that the definition of a common language offers several benefits throughout the RE lifecycle. It provides an opportunity for the early identification and prediction of emergent system attributes required for engineering quality dependability requirements. It also provides an integrated environment for the development of systematic processes of designing dependable systems and the related metrics and measures, i.e. the Science of Design of dependable systems. Furthermore, the

definition of a common language can be reused across multiple systems with support for the incorporation/traceability of changes in policies, regulations, functional and non-functional requirements, and the real-world goals of the system.

As part of our future work we would like to address the following on-going research objectives: 1) Systematically identify the emergent properties of the system based on the evidences collected from various system models to establish the value of “objects”, and their influences and interdependencies in the definition of a common language; 2) Establish metrics and measures of dependability based on the understanding and reflected language from various dimensions of a common language; and 3) Systematically analyze various system models within our framework to identify the “objects of interest” that affect dependability, accuracy, performance, usability, efficiency, criticality etc.

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